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Abstract

Network wireless communication is pervasive in our daily life. At the same time, there is a growing concern related to the impact of the electromagnetic (EM) field emissions on public health. Decision makers require quantitative tools in order to design wireless networks that simultaneously address needs in telecommunications and the health concerns of the population. This paper aims at making a contribution in this sense, by showing how service quality can be provided while minimizing electrosmog for 3G network planning. The method proposed addresses the complete network configuration of Base Stations and antennas in the downlink case, i.e., location and height of each Base Station, as well as tilt and orientation of each antenna hosted on the Base Station. Moreover, in order to minimize EM field intensity, the maximum emitted power for each antenna is also considered as an independent variable. We present an efficient methodology based on a parallel cooperative meta-heuristic framework. The approach combines the use of several Tabu Search threads, each working on few configuration parameters, with a Genetic Algorithm handling all parameters, and uses a central memory to exchange asynchronously solutions and to guide the search of the different threads. Computational results on a realistic instance show the efficiency and robustness of the approach.

Keywords: 3G wireless networks, integrated design, electrosmog minimization, parallel cooperative meta-heuristic search.

Résumé

Les réseaux de communications sans fils sont omniprésents dans la société contemporaine. Simultanément, cependant, on observe des préoccupations de plus en plus vives relativement à l'impact sur la santé des champs électromagnétiques associés à ces réseaux. Il y a donc un besoin pour des outils d'aide à la décision qui traitent à la fois les besoins en télécommunications et les préoccupations de santé publique. Cet article s'inscrit dans cette démarche et montre qu'on peut concevoir des réseaux 3G sans fils qui à la fois assurent la qualité de service du réseau et minimisent la pollution électronique. La méthode proposée considère la configuration complète des stations et antennes : localisation et hauteur de chaque station, ainsi que l'inclinaison et l'orientation de chaque antenne montée sur une station. De plus, la puissance maximum de chaque antenne est également considérée, ce qui permet de traiter, et minimiser, l'intensité du champ électromagnétique associé. Nous proposons une méthodologie efficace, basée sur le concept de recherche méta-heuristique parallèle coopérative. La méthode combine plusieurs recherches avec tabous, chacune travaillant sur une sous-configuration particulière, et une méthode génétique traitant des configurations complètes. Les recherches individuelles échangent de l'information de façon asynchrone, par l'intermédiaire d'une mémoire centrale, ce qui permet de mettre en œuvre un mécanisme de guidage de la recherche globale. Les résultats expérimentaux obtenus à partir de problèmes de dimensions réalistes démontrent l'efficacité et la robustesse de la méthode proposée.

Mots clés : Réseaux sans fils 3G, conception intégrée, minimisation des émissions de champs électromagnétiques, recherche méta-heuristique parallèle coopérative.

1. Introduction

The high quality standards nowadays required for cellular communication systems can be achieved only by way of a comprehensive design of the system that includes all the relevant parameters which characterize the configuration of Base Stations (BSs) and antennas of the network. The majority of the contributions on optimal network planning focuses on locating BSs according to the best tradeoff between network infrastructure costs and service coverage [10,12], whereas the ElectroMagnetic (EM) field level is not explicitly considered. However, the raising concern about serious consequences on human health due to the exposure to EM fields [4] has lead towards precautious regulations and stricter controls enforced by public administrators [1]. Furthermore, people expect high quality services but behave according to the Not-In-My-Back-Yard principle when it comes to BS location. Therefore, EM pollution, so called *Electrosmog,* should be considered an important issue when network planning is carried out. This paper aims at making a contribution in this sense, by showing how service quality can be granted while minimizing Electrosmog. It also generalizes previous works [13] by addressing the complete network configuration of BSs and antennas in the downlink case. By a complete network configuration we mean location, height of each BS, and tilt and orientation of each antenna hosted on the BS. Moreover, in order to minimize EM field intensity, the maximum emitted power for each antenna is also considered as an independent variable in this study.

The computation of emitted power in third generation (3G) networks requires an insight into how the Power Control (PC) mechanism dynamically adjusts power with respect to traffic, making coverage and capacity interdependent issues [9]. Indeed, according to the wide-band code division multiple access (W-CDMA), that is the radio access scheme adopted in UMTS, a new mobile station activated in a cell causes both intra-cell and inter-cell interference in the channel as all connections exploit the same frequency band. The former occurs due to multi-path propagation and despite the orthogonality of the spreading codes. PC permits to keep interferences under control by allowing the BS to dynamically raise emitted power just to the minimum level required in order to keep all connections active. Only once the upper power limit available has been reached, a mobile too far from the BS may loose its connection. Therefore, given a maximum total emitted power, cell coverage depends on traffic distribution. However, the majority of studies [11,12] compute BS emitted power for feasibility purposes as a check on signal quality, but do not consider it as an independent decision variable. In this study we explicitly adjust maximum total emitted power in accordance to PC. Since EM field distribution is affected by all other technical antenna's parameter values besides location and power, a smart choice of appropriate configurations helps to reduce the total needed power. While previous studies addressed the issue of BS configuration [2], to our knowledge this is the first that takes Electrosmog into account.

The aim of this paper is to devise a complete BS network configuration so that the required service quality is guaranteed with minimal impact on the environment from the EM point of view. We provide additional flexibility to the decision maker by considering the setting of each individual antenna as independent from the others, even when hosted at the same BS. At the same time, we handle technological issues peculiar of 3G systems as PC and soft handover. Existing sequential algorithms do not address adequately the complexity of the problem; therefore we investigate the potential of sophisticated parallel meta-heuristics as a solution approach.

In section 2 the optimization problem is formalized, the architecture of the proposed cooperative meta-heuristic method is introduced in section 3; finally, section 4 presents computational results comparing the performance of sequential vs. parallel cooperative methods for this particular problem.

2. The planning problem

The cellular network planning problem addressed in this paper can be defined as follows: given a geographical area in which the coverage of a 3G system service is required, the area is discretized by way of a regular grid of Test Points (TPs); a traffic demand is also given (represented by an Erlang traffic value associated to every TP), together with a set of BSs each equipped with either sectorial or omnidirectional antennas and associated to a set of locations. Several configurations are possible for each antenna by combining all allowed different values of each parameter. Along with BS location, the optimal parameter setting for each antenna is searched for in order to minimize the environmental impact of the total EM field level while guaranteeing the required quality standard. The considered parameters are: transmitted power level of each antenna, sector orientation (respect North), angle of vertical mechanical tilt of each antenna, and BS electrical center height and location.
A realistic representation of the network requires an accurate EM field simulator in order to estimate the electric field produced by each antenna and compute the global effect at each TP due to the interaction of all emission sources.

2.1 Electromagnetic field simulator

In radio communication, electromagnetic waves interact with the external environment, causing attenuation in the received signal. The proper evaluation of the attenuation is a crucial aspect of wireless network planning. Several different radiopropagation methods can be used to estimate the mean intensity value of the received signal in a specific point. Such methods evaluate the attenuation (or path loss L) as the transmitted-to-received power ratio, accounting also for possible wave interactions with the obstacles located in between transmitter and receiver.

The methods considered in the EM simulator [3] are: Free Space Loss, the empiric method COST231-Okumura-Hata and semi-empiric COST231-Walfisch-Ikegami model.

The accuracy of the results obtained by such methods is strictly related to the application environment. Therefore, the choice of the right model in each situation is a very critical and delicate aspect. In general, empirical models are recommended when there is a lack of detailed information about the area. They require low computational effort, but the accuracy depends not only on the empirical measurement precision but also on the similarity between the analyzed environment and the model reference one. Semi-empirical models take into account average characteristics of the environment (e.g., mean building height, mean street width, and so on) and propagation principles (e.g., diffraction), so they provide more realistic estimations than empirical models, but accuracy depends on the homogeneity of the area. The Free Space Loss model may also be fitting in some situations; as it overestimates the E field value, it can be useful for radioprotection purposes (worst case). Moreover it can be used when the information about the area is unknown or when a fast approximation of the field level is required.

For each TP i and source sc located at distance r from i, the EM field at i due to sc is $\underline{E}^i_{sc} = E^i_{sc} e^{-jkr}$, where k is the propagation vector. Its estimated module

$$E^i_{sc} = \frac{480\pi^2 \cdot P_tot \cdot G_T}{\lambda^2 \cdot L}$$

depends on the path loss L (computed according to one of the abovementioned models depending on the territory from source to TP), on the total emitted power P_tot, on the gain of the transmitted antenna G_T, and on the wavelength λ. The contributions of different antennas working at the same

frequency are added by complex sum, while the total EM level (E^i_{tot}) sensed at TP i due to all active sources in the area is given by the quadratic sum of the module for each frequency.

2.2 Constraints

The following constraints model the relations that must hold in order to provide a realistic representation of a 3G cellular network, impose upper limits on EM field values, and ensure the required quality standards for the downlink case.

Let $SBS=\{s\}$ be the set of BS considered, $SC(s)=\{sc\}$ the sectors of each BS, and $STP=\{i\}$ the TP set. The values of all technical parameters are bounded within a given range and discretized according to a prearranged step, so that each parameter of the configuration of each BS and antenna varies within a discrete set. The product of all parameter sets for a given sector sc of a BS s yields its possible configurations, and the union over all antennas and BSs is the set of all potential network configurations. Only feasible ones correspond to valid network configurations. Feasibility is enforced by the following constraints. The first one is related to radioprotection: at every TP i, the total field due to all the BSs has to be less than a threshold E_{max} fixed by safety standards:

$$E^i_{tot} \le E_{max} \quad \forall i \in STP \quad .$$

In order to model the working mechanism of UMTS systems, let us introduce the *cell* of sector sc as the set of TPs where the normalized pilot signal strength NPS_{sc} exceeds a fixed threshold SN_{pilot}. NPS_{sc} is defined as the ratio of received pilot energy to overall received downlink energy due to the sector sc:

$$NPS_{sc} = \frac{P_pilot_{sc}/W}{FN_{th} + Int}$$

where P_pilot_{sc} is the received power from the pilot channel of sector sc, W the bandwidth (1.25 MHz), F the BS noise figure (5 dB), N_{th} the thermal noise power density (-174 dBm) and Int interference due to the other sectors: $Int = \sum_{sc' \neq sc} (P_{sc'}/W)$ with $P_{sc'}$ received power from sector sc'.

When checking solution feasibility, cell connection is verified assuming a 4 grid adjacency (such that i and j are adjacent $\Leftrightarrow |i_x - j_x| + |i_y - j_y| = 1$ and $(i_x - j_x)\cdot(i_y - j_y) = 0$). Cell points are visited recursively, starting from the TP nearest to the main beam direction of the antenna and proceeding to its adjacent points. Each point is tested to verify whether the signal-to-noise ratio is over the minimal threshold. In such a case, if all its adjacent points meet the condition, then the point belongs to the cell otherwise it is a border point of the cell. Note that cells may overlap. Based on cell topology, handover and downlink capacity can be tested.

According to soft handover, the mobile receives signals from more than one sector at the same time and it combines them to avoid the handover muting effect of hard handover when moving from one sector to another one. Feasibility requires at least intersection among cells at border points. Grid step may be intensified along cell borders if needed, so that this check is not biased by the step size.

The downlink capacity constraint is evaluated according to PC mechanism, and considering the so called figure of merit M, i.e. the difference between the received and required signal-to-noise ratio with

respect to all the BS channels (pilot, synchronization, paging and traffic channels) of a sector *sc* at every TP.

Total emitted power *P_tot* is divided among the different channels by assigning about the 15-20% of *P_tot* to *P_pilot*, about 10% and 30-40% to *P_sync* and to *P_paging*, respectively, and the remainder to *P_traffic_tot*, which is dedicated to serve all active mobiles in the cell.

To evaluate the signal-to-noise ratio the number of active users has to be estimated. This number, N_{sc}, can be derived from traffic demand, which in turn depends on the topographic characteristics of the area. A common practice is to estimate the active user number N_{sc} as the most probable value according to a Poisson distribution and to assign to each user an equal fraction of *P_traffic_tot*.

A more realistic modeling of the PC mechanism can be achieved by partitioning cell users into three sets depending on their distance from the antenna (near, medium and far), and assuming that near users require less power than those in the medium area, who in turn require less than those far.
The signal-to-noise ratio for every BS channel is given by:

$$\left(\frac{E_b}{I_0}\right)_{ch}^{i,sc} = \frac{P_ch_{sc}^{i} / R}{FN_{th} + (I_{in} + I_{out})}$$

where $P_ch_{sc}^{i}$ is the received power of channel *ch* of the sector *sc*, *R* channel rate, I_{in} and I_{out} interference from the same sector and from outer sectors. Since the pilot channel doesn't carry information, energy per chip (E_c) has to be considered rather than energy per bit (E_b). In this case the formula is stated with respect to bandwidth instead of channel rate *R*. The constraint can be described by the following inequalities:

$$M_{pilot}^{i,sc} = \left(\frac{E_c}{I_0}\right)_{pil}^{i,sc} - SN_{pilot} > 0 \qquad M_{traffic}^{i,sc} = \left(\frac{E_b}{I_0}\right)_{tr}^{i,sc} - SN_{traffic} > 0$$

$$M_{sync}^{i,sc} = \left(\frac{E_b}{I_0}\right)_{sync}^{i,sc} - SN_{sync} > 0 \qquad M_{paging}^{i,sc} = \left(\frac{E_b}{I_0}\right)_{pag}^{i,sc} - SN_{paging} > 0$$

All the abovementioned relations are required for system feasibility, so they will all be enforced as constraints in our solution approach. Moreover, as perfect link balance is achieved when all the *M* values are equal to zero, solutions whose *M* values are as close to 0 as possible will be sought after.

2.3 Objective functions

The objective function aims at modeling the electromagnetic impact on the environment due to the emissions of the BSs of the network and other potential sources in the area. Several scalar measures can be implemented to capture this goal. We propose the five following functions, partially inspired by practitioners: *MinSum* (the sum over all TP of the total E-field level), *MinMax* (the maximum E-field value in the area), *Min30%Max* (the sum of E-field levels over the 30% of TP with highest field value (STP_+)), *Min30%Min* (the sum of E-field levels over the 30% of TP with lowest field value (STP_-)) and *MinDiff* (the difference of the total E-field in STP_+ and STP_-). Each definition has pros and cons. *MinSum* addresses the average value but ignores peaks, *MinMax* targets the highest peak but disregards all other points. The next two consider the mean over the set of highest and lowest values, respectively, while the last aims at smooth field distributions although it may increase average field level.

Note that the effect of the variation of any of the attributes of the configuration can not be predicted a priori with respect to any function. The behavior of the different objective functions has been studied [14]. No particular dominance emerged among the functions, but every one provides interesting solutions for the decision process. This complementarity may be exploited in the cooperative framework by taking one function as the principal objective and using the other ones to diversify the search towards as yet uncharted regions. However, in the current experiments just *MinSum* will be used as an objective function.

3. The proposed cooperative solution approach

Two sequential meta-heuristics were developed and hybridized in a previous study [13], i.e., a Tabu Search (TS) [5] and a Genetic Algorithm (GA) [6]. However this methodology was addressing a limited subset of parameters, namely location and power. When complete configurations were considered, it did not perform in a satisfactory manner. Consequently, we are proposing a parallel cooperative solution framework that generalizes an approach that proved successful for BS location and power setting. Indeed, parallel meta-heuristics allow to address very large size problems and, when combined into cooperative structures, can exploit shared knowledge and different search patterns in order to provide robustness [7].

3.1 Sequential algorithms

Before introducing the cooperative framework, the sequential TS and GA procedures are quickly sketched.

In GA, a solution (chromosome) represents a binary coding of an antenna configuration. The length of the chromosome depends on the possible values parameters can assume and on the number of BSs. The initial population is created randomly. The offspring is obtained from the main population by selection (by way of a tournament with respect to the objective value), reproduction and mutation mechanisms. In the reproduction phase the creation of descendants is carried out by crossover. Different types of crossover are implemented: one-point, two-points, uniform and gene-uniform crossover. The one-point crossover is an operator that randomly selects a point within a chromosome then interchanges the two parent chromosomes at this point to produce two new offsprings. The two-point crossover uses the same technique randomly selecting two points instead of one. The uniform crossover decides with some probability which parent will contribute each of the bit values in the offspring chromosomes. This allows the parent chromosomes to be mixed at the bit level rather than the segment level. For some problems, this additional flexibility outweighs the disadvantage of destroying building blocks. A gene is the smallest part of the chromosome with an associated information (in our case the power emitted value of a sector, a position, and so on). The gene-uniform crossover works as the uniform one but at gene level, in order to preserve building blocks. After reproduction, mutation occurs. This phase is very important because it provides genetic diversity and it enables GA to enlarge the search to a broader space.

A solution in the Tabu Search algorithm represents a specific network configuration. When a partial neighbourhood is considered, some of the configuration parameters are kept fixed. The basic procedure of a TS algorithm goes from the current solution to the next by a transformation called *move*. In our implementation, a move is obtained by raising or decreasing of one level the value of each parameter. The neighbourhood is given by all possible combinations of these variations on the parameters that are being optimized in a given procedure. Exhaustive enumeration of very large neighborhoods should be avoided. Since checking solution feasibility is the most time consuming part of a solution evaluation,

the neighborhood exploration is carried out so that feasibility is tested only once other necessary requirements are satisfied. As usual in TS, once a move is performed, the reversal move is forbidden for 'tabu size' steps. Since a move affects the topology of a cell, the tabu tag of its reversal is decreased whenever another move modifies the same cell.

The TS procedure is enhanced by several mechanisms to improve the quality solution and the speed: k-improvement technique, short term memory intensification and diversification, long term memory diversification, and tabu status cancellation [8].

3.2 The cooperation mechanism

The cooperative framework [8] combines the use of several TS threads each working on few parameters with a GA that improves all the parameters, using a central memory to exchange asynchronously solutions and to guide the different thread searches.

The global search is divided into three phases:

1. *Initial phase*: different TS threads, each optimizing a different subset of configuration parameters, start their individual search from randomly generated feasible solutions; the improving solutions of each TS are sent to the central memory to build the initial population of the GA;

2. *Intermediate phase*: threads send their good solutions to the central memory, where they are sorted and sent to the threads when required for diversification purposes;

3. *Orientation phase*: the selection of solutions sent to the threads is guided by the trend indicators extrapolated from the solutions presented in the central memory.

The timing and the solutions involved in the exchanges between the threads and the central memory are described in Table I.

<table>
<tr><th></th><th>GA</th><th>TS</th></tr>
<tr><td>Threads to pool</td><td>On improvement or after a fixed number of generations</td><td>Every time a new improving solution or a local optimum is found</td></tr>
<tr><td>Sent solutions</td><td>Best solutions (top 10%)</td><td>Improving and local optima</td></tr>
<tr><td>Pool to threads</td><td>Before parents selection</td><td>For diversification/orientation phases</td></tr>
<tr><td rowspan="3">Received solutions</td><td>Initial phase:
initial population collected from different TS threads</td><td rowspan="2">Intermediate phase:
(1) a solution different from the current one and from the temporary best (or a feasible mode configuration) from the elite part of Sorting 1</td></tr>
<tr><td>Intermediate phase:
different and good solutions from elite part of Sorting 1</td></tr>
<tr><td>Orientation phase:
different and good solutions from elite part of Sorting 2</td><td>Orientation phase:
(1) a solution different from the current one and from the temporary best (or a feasible mode configuration) from the elite part of Sorting 2
(2) fixed parameters</td></tr>
<tr><td>Received solution management</td><td>The new solutions are added to the current population</td><td>If (1), path relinking
If (2), fixed values are forced in the current solution</td></tr>
</table>

Table I
Cooperation mechanism

The solutions in the central pool are managed according to the following mechanisms:

- Sorting: once a new set of solutions has been added to the pool, all solutions are sorted with respect to two criteria, depending on the phase: objective value (Sorting 1) and the quality of the link balance (Sorting 2); solutions are then selected depending on their rank (highest) and on how many times the solution has already been sent (lowest);

- Enforcing diversity: sending configurations with different characteristics is crucial; this is carried out by comparing solutions with a reference one (e.g., the best of a specific thread) with respect to the cell distribution; the objective value is not a sufficient indicator for diversity because different configurations can bring to similar objective values;

- Extrapolation of common characteristics: during the search process, the best solutions according to each searching criteria are used to extrapolate two indicators that identify the main characteristics of each specific sorting. The mode configuration indicator is a complete network configuration formed by the mode value of each parameter; the fixed parameter indicator is made of the values of the parameters exceeding a given threshold.

Both indicators are used for the diversification phase of the TS threads. Particularly, when the solution corresponding to the mode indicator is feasible, it is used as target for a path relinking procedure starting from the current configuration. Path relinking permits to visit solutions laying on a path from an initial solution to a target one, in order to discover good and not yet visited solutions. It is a strong diversification action in this framework because it allows to change the complete set of parameters even though the TS works only on a subset. Fixed parameters are used during the orientation phase to guide the search

4. Computational results

We consider an instance of an UMTS provider network within an area of 25 km^2 with a medium density of 700 inhabitants/km^2. The radiopropagation method is COST231-Okumura-Hata and the objective function is *MinSum*. 100 TPs have been considered. Each BS location can be selected among 8 different positions and 8 height levels between 10 and 30 m are considered. Concerning the sector parameters, the emitted power is discretized in 16 levels between 0 and 30 W, the tilt in 8 levels between 0 and 8°, and the orientation of each sector in 16 values with a step of 7,5°. Several models of antenna commercially available have been used at different BSs.

We compare the sequential heuristics and the parallel one. Tables II and III report the results from 5 repetitions of GA and TS algorithms on the same instance, starting from different initial solutions. Times are reported in CPU seconds on a 1.2 GHz machine. A maximum number of iterations/generations has been fixed to compare the sequential outcome with the cooperative one (Table VI). Note that the TS results have been obtained optimizing only on a subset of parameters. Also, when the sequential GA works on the complete configuration, the generation of the initial population requires a very long time. These two drawbacks are overcome by the cooperative parallel structure. The results indicate that the cooperative procedure not only outperforms the individual algorithms but also provides the best results over repeated runs of the sequential algorithms. Note that the computational time of the cooperative method is comparable to that of the GA excluding the time required by the initial population generation.

Figure I displays field distributions that correspond to marked solutions appearing in Tables II to IV. As the pictures clearly report, the solution obtained by the cooperative framework has a lower environmental impact from the EM point of view compared to the sequential solutions.

BEST SOLUTION COST	TIME (s) (generation initial population + iterations)	NOTES
0.114841	2915 (2012+903)	- complete configuration optimization - in the initial population at least 4 feasible configurations have to be generated - 120 generations
0.096719	2159 (1239+940)	
0.100386	1531 (635+676)	
0.100927 (A)	1784 (1136+648)	
0.111225	2212 (1298+914)	

Table II: GA results illustrate the computational effort required to generate the initial population

BEST SOLUTION COST	TIME (s)	OPTIMIZING PARAMETERS	NOTES
0.106158	342	emitted power and position	- a subset of parameter is optimized - initial random solution - 100 iterations
0.112666	326	" "	
0.079612	472	emitted power and orientation	
0.080892 (B)	398	" "	
0.079602	572	" "	

Table III: TS results on specific subset of parameters

BEST SOLUTION COST	TIME (s)	COOPERATIVE FRAMEWORK
0.060366 (C)	699	- *processor 0*: pool management - *processors 1-4*: 4 TSs that work on different subsets of parameters, with different settings for 100 iterations - *processors 5-6*: 2 GAs with 100 individuals (the first with 120 generations, the second with 100 generations and starting during the orientation phase with the elite solutions of Sorting 2 as initial population)
0.058602	747	
0.071148	1123	
0.057080	857	
0.059697	1038	

Table IV: Cooperative search results

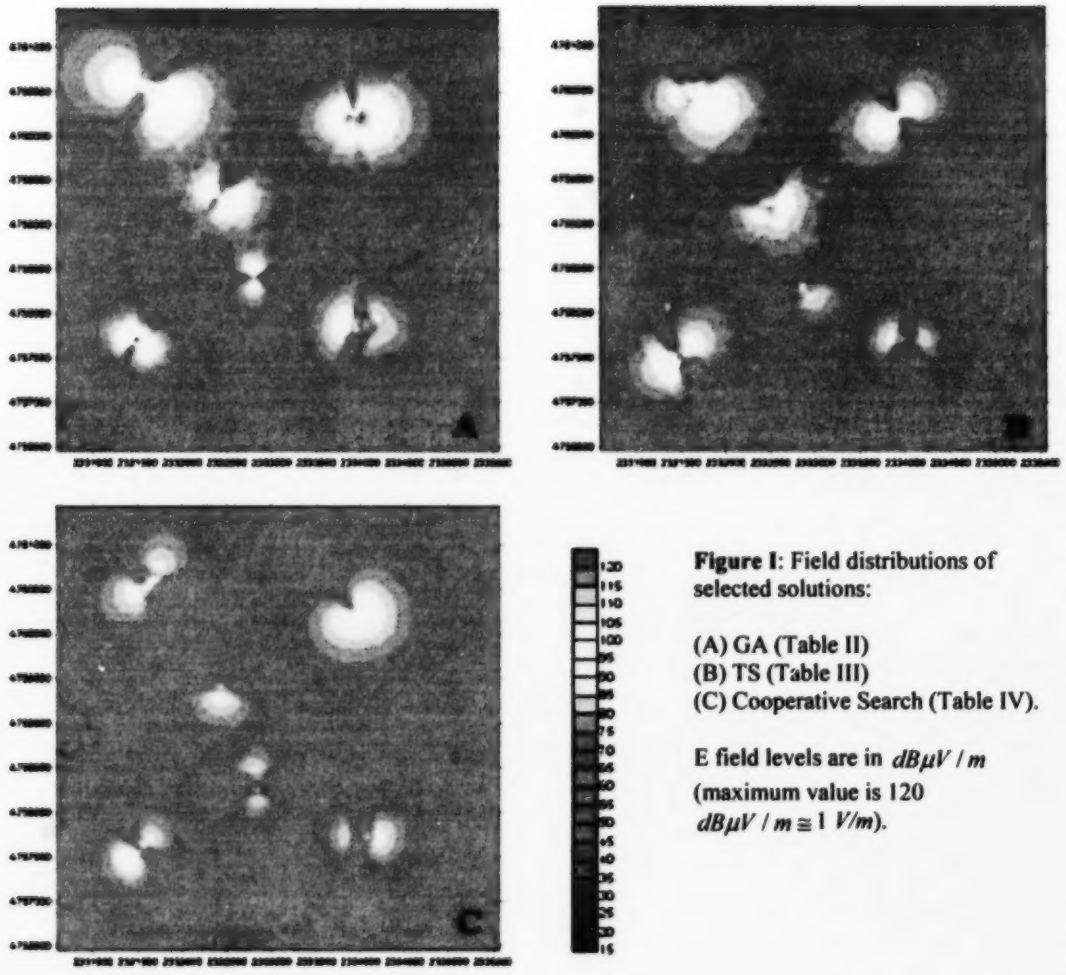

Figure I: Field distributions of selected solutions:

(A) GA (Table II)
(B) TS (Table III)
(C) Cooperative Search (Table IV).

E field levels are in $dB\mu V / m$ (maximum value is 120 $dB\mu V / m \cong 1\ V/m$).

5. Conclusions

We have described a methodology that provides the means to devise a complete configuration of BSs and antennas in 3G systems with the specific objective of minimizing the environmental impact of EM emissions. The cooperative parallel meta-heuristic proposed proved to be able to cope with the high number of variables involved in the tuning of all the configuration parameters that are required for an accurate network planning. The proposed method permits to explore in depth the solution space and to direct the search towards specific areas exploiting indicators extrapolated from solutions previously encountered.

The application to a realistic case shows good adaptability of the method. The resulting network configuration displays a very low field level distribution. We believe that such a tool may support the decision maker in planning 3G networks that simultaneously meet the technological requirements and address the health concern of the population.

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